

Low Frequency Gravitational Waves from White Dwarf MACHO Binaries

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ABSTRACT

The possibility that Galactic halo MACHOs are white dwarfs has recently attracted much attention. Using the known properties of white dwarf binaries in the Galactic disk as a model, we estimate the possible contribution of halo white dwarf binaries to the low-frequency (10^{-5} Hz $< f < 10^{-1}$ Hz) gravitational wave background. Assuming the fraction of white dwarfs in binaries is the same in the halo as in the disk, we find the confusion background from halo white dwarf binaries could be five times stronger than the expected contribution from Galactic disk binaries, dominating the response of the proposed space based interferometer LISA. Low-frequency gravitational wave observations will be the key to discovering the nature of the dark MACHO binary population.

Subject headings: gravitation — white dwarfs — dark matter

1. Introduction

The MACHO project has detected 13-17 gravitational microlensing events in the direction of the Large Magellanic Cloud to date (Alcock *et al.*, 2000), while the EROS collaboration has detected two (Lasserre *et al.*, 1999). One result of the analysis of the observations (Alcock *et al.*, 2000) is that, independent of the halo model assumed, there are of order 2×10^{11} MACHOs of mean mass $0.5M_{\odot}$ in the Galactic halo.¹

While the microlensing observations have confirmed the existence of MACHOs (Massive Astrophysical Compact Halo Objects) in the halo, the actual nature of these objects is still a matter

¹It is noteworthy that this number is similar in magnitude to the number of stars in the Galaxy.

of much debate. The mass suggests main sequence red dwarf stars, but these appear to be ruled out observationally (Bahcall *et al.*, 1994; Graff & Freese, 1996a; Graff & Freese, 1996b). Until recently, white dwarf stars also seemed to be a highly unlikely MACHO candidate, since observations of the Galactic halo (see, *e.g.*, Flynn *et al.*, 1996) did not find a population of old, red, white dwarf stars. Since conventional baryonic stars seemed to be ruled out, highly speculative candidate objects have been proposed as MACHO models, such as primordial black holes and boson stars.

Recently, however, new models of white dwarf cooling processes indicate that old, cool, white dwarf atmospheres form molecular hydrogen, which can strongly absorb red light. This implies that aging white dwarfs will be blue objects, rather than red as was previously believed (Saumon & Jacobson, 1999; Hansen 1999). In light of these new cooling models, predictions have been made for the number of halo white dwarfs that should be seen in deep field surveys (Richer, 1999), and new analyses have detected candidate halo white dwarfs with blue colors in the Hubble Deep Field (Ibata *et al.*, 1999; Méndez & Minniti, 2000). In addition, local blue white dwarfs with large proper motions, indicating that they are members of the halo population, have been tentatively identified (Ibata *et al.*, 2000).

In this Letter we assume that the halo MACHOs are white dwarf (WD) stars, and estimate the low frequency (10^{-5} Hz $< f < 10^{-1}$ Hz) gravitational wave (GW) background that would be produced from a halo population of white dwarf binaries. Such a background could be an important source for space-based laser interferometer gravitational wave detectors such as the proposed LISA mission (Bender *et al.*, 1998). Gravitational waves from halo WD binaries could be a very interesting signal (if one is interested in characterizing the binary population of MACHOs) or a serious confusion noise source (if one is concerned that this background is masking signals from other sources of interest, such as a cosmological background of GW). Estimates of the gravitational wave signal from a halo composed of primordial black holes has shown that the signal from binaries in the halo could dominate the output of an interferometer such as LISA (Hiscock, 1998; Ioka *et al.*, 1999).

In the absence of any observational evidence concerning the properties a halo population of binary WDs, we make the assumption that white dwarf binary properties in the halo mimic those of Galactic disk WD binaries (Hils, Bender & Webbink, 1990; Bender & Hils, 1997). This assumption is almost certainly incorrect; the halo WD population is generally felt to be much older than the disk population, and (based on the microlensing events) probably has a mass distribution that differs from the disk WD population. However, using the disk as a model is the best one can currently do.

2. Disk binaries as GW sources

The GW background generated by disk binaries (both Galactic and extragalactic) has been thoroughly studied by Hils, Bender, and Webbink (Hils, Bender & Webbink, 1990; Bender & Hils,

1997). They have made careful estimates of the GW signal due to Galactic disk WD binaries and also that due to extragalactic binaries. In recent work, they have combined these signal amplitudes with the planned properties of LISA to generate a simulation of LISA’s response to the combined Galactic and extragalactic signals. The key factor in this analysis is the width of a frequency bin in the LISA data analysis for periodic sources. With a one-year integration time, each frequency bin will have a width $\Delta f = (1 \text{ yr})^{-1} \simeq 3 \times 10^{-8} \text{ Hz}$. At frequencies beginning at around $1 \times 10^{-3} \text{ Hz}$ and higher, the number of Galactic binaries per bin will begin to drop to order unity. At this point, the properties of individual Galactic binaries can be determined and their signal removed from the record, so that the weaker combined signal of extragalactic binaries will begin to be observable in the open bins. Solving for a particular Galactic binary and removing it from the data record will typically require three bins of information (Hellings, 1996). The effective spectral amplitude observed by LISA, h_f , after taking the finite bin width into account, is given by (Bender & Hils, 1997)

$$h_f = \left(\frac{(h_f^e)^2 \left[(h_f^G)^2 + (h_f^e)^2 (1 - e^{-3r}) \right]}{e^{-3r} (h_f^G)^2 + (h_f^e)^2 (1 - e^{-3r})} \right)^{1/2}, \quad (1)$$

where r is the number of Galactic binaries per frequency bin, h_f^G is the spectral amplitude of the Galactic binary background, and h_f^e is the spectral amplitude of the extragalactic binaries.

Using the relation between the spectral amplitude and the number of binaries per unit frequency dN/df , the GW luminosity of a binary $L(f)$, and the average inverse distance squared $\langle d^{-2} \rangle$,

$$h_f(f) = \frac{2}{\pi f} \left[\left\langle \frac{1}{d^2} \right\rangle L(f) \frac{dN}{df} \right]^{1/2}, \quad (2)$$

it is possible to extract an estimate of dN/df from the Bender-Hils results, along with an approximation to the spectral amplitudes of the backgrounds due to Galactic disk binaries and extragalactic binaries. We find that the Bender-Hils results are well approximated by

$$\frac{dN}{df} \simeq 4.47 \times 10^{-3} f^{-11/3}, \quad (3)$$

$$\log_{10}(h_f^G) = - \left(\frac{7}{6} \right) \log_{10}(h_f) - 21.8, \quad (4)$$

and

$$\log_{10}(h_f^e) = - \left(\frac{7}{6} \right) \log_{10}(h_f) - 23.0 \quad (5)$$

where the frequency f is measured in Hz. The frequency dependence in these equations is characteristic of a population of circular binaries that is evolving solely due to gravitational radiation reaction.

3. Rescaling the Disk to the Halo

A simple estimate of the gravitational wave background expected from binary WDs in the halo can be obtained by assuming that the WD binary population of the halo is similar in nature to that of the disk. One can estimate the halo GW background by rescaling the disk binary WD population, based on three factors:

1. The ratio of the total number of halo WD MACHOs to the total number of Galactic disk WDs, $N_{\text{halo}}/N_{\text{disk}}$.
2. The ratio of the average inverse distance squared of a halo MACHO to the average inverse distance squared of a disk WD, $\langle d^{-2} \rangle_{\text{halo}}/\langle d^{-2} \rangle_{\text{disk}}$.
3. The ratio of the fraction of white dwarfs in binaries in the halo to the fraction of white dwarfs in binaries in the disk, α .

The number of WDs in the disk is computed by integrating over the standard cylindrical exponential model,

$$\rho = \rho_0 \exp \left[\frac{-r}{r_0} \right] \exp \left[\frac{-|z|}{z_0} \right], \quad (6)$$

where $r_0 = 3.5$ kpc and $z_0 = 90$ pc are the exponential scale heights for the WD population in the disk (Hils, Bender & Webbink, 1990), and $\rho_0 = 4.72 \times 10^{-2} \text{ pc}^{-3}$ is the number density of white dwarfs at the center of the galaxy (computed from the local density of white dwarfs in the solar neighborhood, $\rho_{\odot} = 4.16 \times 10^{-3} \text{ pc}^{-3}$ given in Knox, Hawkins & Hambly, 1999). Integrating the disk WD density using the distribution in Eq. (6) yields

$$N_{\text{disk}} = 6.5 \times 10^8 \quad (7)$$

for the disk population.

We assume that the number of MACHOs in a 50 kpc halo (to the LMC), is $N_{\text{halo}}^{50 \text{ kpc}} = 2 \times 10^{11}$, the halo-model-independent result obtained by the MACHO collaboration (Alcock *et al.*, 2000). For a larger halo, extending some 300 kpc (halfway to M31), this number can be scaled by assuming that the spatial distribution of white dwarf MACHOs follows the standard spherical flat rotational halo model given by

$$\rho = \hat{\rho} \frac{R^2 + a^2}{r^2 + a^2}, \quad (8)$$

where $\hat{\rho}$ is the local density of dark matter, r is the Galactocentric radius, $R = 8.5$ kpc is the Galactocentric radius of the Sun, and $a = 5.0$ kpc is the halo core radius. Integrating Eq. (8) out to 50 kpc and setting the number of MACHOs equal to 2×10^{11} , one obtains $\hat{\rho} = 0.0094 \text{ M}_{\odot} \text{ pc}^{-3}$. Using this value and integrating Eq. (8) out to 300 kpc gives

$$N_{\text{halo}}^{300 \text{ kpc}} = 1.3 \times 10^{12}. \quad (9)$$

The average inverse distance squared between sources and the Sun, $\langle d^{-2} \rangle$, may be found by integrating over the source distributions given in Eqs. (8) and (6). Expressing the result as a distance, one finds that for the disk,

$$\langle d^{-2} \rangle^{-1/2} = 4.85 \text{ kpc} , \quad (10)$$

while

$$\langle d^{-2} \rangle^{-1/2} = 15.7 \text{ kpc} \quad (11)$$

for a 50 kpc halo, and

$$\langle d^{-2} \rangle^{-1/2} = 39.5 \text{ kpc} \quad (12)$$

for a 300 kpc halo.

Nothing is presently known about the ratio of the fraction of white dwarfs in binaries in the halo to the fraction of white dwarfs in binaries in the disk, α , so we leave this as a free parameter in our model, and examine the consequences of different values for α .

In rescaling the disk background GW spectrum, there are two separate effects associated with the potentially larger number of WD binaries in the halo. First, the larger number tends to raise the overall level of the halo background relative to that of the disk. Second, since there are more halo binaries per unit frequency interval, this pushes the point in the spectrum where one first encounters open frequency bins (one or fewer Galactic halo binaries per bin), to higher frequencies than in the disk. Scaling the number of Galactic disk binaries by multiplying by the ratio of the total number of WDs in the halo to the number in the disk yields

$$\log_{10} \left(\frac{dN}{df} \right)_{\text{halo}} = - \left(\frac{11}{3} \right) \log_{10}(f) - 2.35 + \log_{10} \left(\frac{\alpha N_{\text{halo}}}{N_{\text{disk}}} \right) . \quad (13)$$

The overall level of the GW backgrounds from Galactic halo WD binaries and extragalactic halo binaries will scale according to

$$h_f^{\text{halo}} = K(\alpha) h_f^{\text{disk}} , \quad (14)$$

where the scaling factor $K(\alpha)$ is defined as

$$K(\alpha) = \left[\alpha \frac{N_{\text{halo}}}{N_{\text{disk}}} \frac{\langle d^{-2} \rangle_{\text{halo}}}{\langle d^{-2} \rangle_{\text{disk}}} \right]^{1/2} . \quad (15)$$

If one assumes that the halo population of white dwarfs precisely mimics the disk population, then the same fraction of WDs will be in binaries in the halo as in the disk, and $\alpha = 1$. In this case the scaling factor is given by

$$K(\alpha = 1) = \begin{cases} 5.42 & \text{for a 50 kpc halo} \\ 5.49 & \text{for a 300 kpc halo} \end{cases} . \quad (16)$$

An estimate of the response of LISA to a background of GW from halo WD binaries can now be obtained by rescaling the Galactic and extragalactic disk spectral amplitudes [Eqs. (4) and (5)] using Eq. (14) with Eq. (13) in Eq. (1). The resulting signal estimate for LISA is illustrated in Figure (1), along with the Bender-Hils estimate for disk binaries for comparison. The signal from the halo WD binaries is substantially stronger than that from the disk binaries. At lower frequencies, the predicted backgrounds for a 50 kpc and 300 kpc halo are indistinguishable in the figure, owing to the similarity in the values of K in Eq.(16). The larger number of halo binaries compared to the disk fills the frequency bins to a substantially higher frequency before one encounters open bins, where weaker signals such as the extragalactic background may be observed. If only the disk background is present, then potential extragalactic sources can be detected above a critical frequency of about 2×10^{-3} Hz, where frequency bins cease to be cluttered with many Galactic binaries. With a 50 kpc halo, the greater number of Galactic binaries increases this critical frequency to about 1×10^{-2} Hz, while for a larger 300 kpc halo, the critical frequency is further increased to about 2×10^{-2} Hz. In the latter case, the frequency at which bins begin to open up and allow weaker extragalactic signals to be detected is roughly equal to where LISA’s instrumental noise curve begins to rise.

Of course, it is presently unknown whether the fraction of WDs in binaries in the halo is comparable to that in the disk. A priori, it could be larger ($\alpha > 1$) or smaller ($\alpha < 1$). One question which can be posed within the present simple model is to ask what value of α will result in the halo GW signal being similar in magnitude and shape to that of the disk. This determines a minimum value for α , above which the halo signal will dominate over that of the disk binaries. Reducing α in Eqs.(13) and 14) one finds that the signal from a 50 kpc halo will be dominant if $\alpha > 10^{-2}$, while the signal strength from a 300 kpc halo would exceed that of the disk if $\alpha > 5 \times 10^{-3}$. This implies that even if the fraction of halo WDs in binaries is as low as 1% of the fraction of disk WDs in binaries, the WD MACHO binaries will be “bright” enough to stand out from the expected signal of the disk binaries. While the numbers here are highly sensitive to the specific details of the halo binary MACHO population, they illustrate that the halo will be a significant source of a low frequency confusion background of gravitational waves unless the fraction of MACHO WDs in binaries is orders of magnitude lower than in the disk.

4. Discussion

While this simple scaled model is certainly not an accurate representation of the Galactic halo binaries, it does illustrate that the GW background from a halo population of white dwarf binaries could easily dominate the signal in a space-based interferometer such as LISA. Further, this result, together with other studies that have considered the GW signal from MACHOs if they were identified with primordial black holes (Nakamura *et al.* 1997; Hiscock, 1998; Ioka *et al.*, 1999; Ioka *et al.*, 2000), demonstrates that whatever the nature of MACHOs, if even a small fraction of them are in binary systems, then they will create a strong confusion noise background which could saturate the frequency range in which LISA is most sensitive (2×10^{-3} Hz $< f < 2 \times 10^{-2}$ Hz).

Some may consider such a prospect discouraging, as the combined signal from abundant halo binaries could mask other weak signals and make them undetectable. This has previously been a serious concern with respect to the disk binaries—hence the name “confusion noise” for a signal that actually describes the short-period binary population of the Galaxy. There has been hope that the confusion noise from Galactic disk binaries could be extracted from the general stochastic (e.g., cosmological) background by utilizing the anisotropic nature of the disk signal (Giampieri & Polnarev, 1997). If there is a substantial signal associated with halo binaries, however, then this scheme will not work. The solar position is sufficiently near the center of a spherical Galactic halo that it would seem difficult or impossible to be able to subtract out the halo confusion noise signal based on its very small anisotropy.

On the other hand, even our simple analysis shows that the GW signal from the halo binaries could be a powerful tool to determine the properties of the MACHO binary population, as well as general properties of the halo itself, such as its size.

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Fig. 1.— The expected response of LISA to the gravitational wave signal from a halo population of white dwarf binaries is shown. The upper solid curve represents a 50 kpc halo; the dashed curve represents a 300 kpc halo. The lower curve is the detailed spectrum predicted by Bender and Hils for disk binaries. The expected sensitivity of the LISA interferometer ($S:N = 1$) is also shown.

